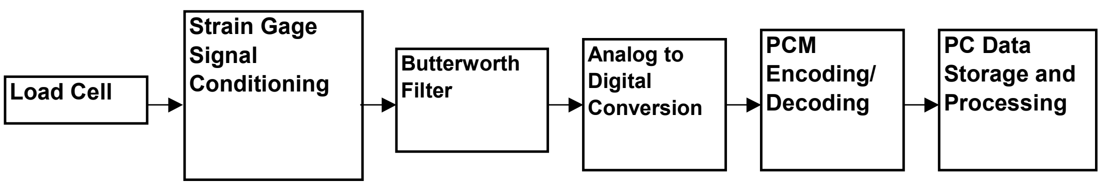
Load Cells (Yaw Moment)

Channel	ID Code	Description
342	NAYM	Nacelle yaw moment

Location	Adjacent to yaw brake caliper; constrains motion of 4-bar linkage where brake caliper is one bar.
Measurement type and units	Tensile and compressive load, N
Excitation	10 Vdc
Range	±10,000 lbs.
Resolution	32 N/bit
Calibration method	Application of known loads (A1)
Sensor description	Hermetically sealed, universal tension and compression force sensor Transducer Techniques Model: HSW-10K



Note: The sign convention is such that positive yaw moment is in the direction of a moment restoring the turbine from negative yaw error to zero degrees yaw error.

Calibration Procedures (See p. B-3)

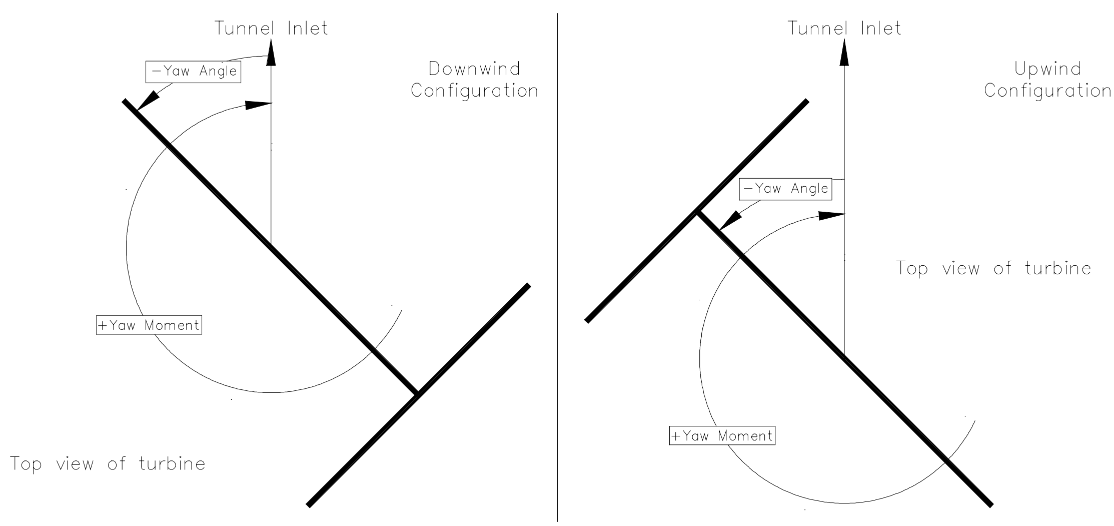


Figure B.1. Yaw moment measurement conventions.

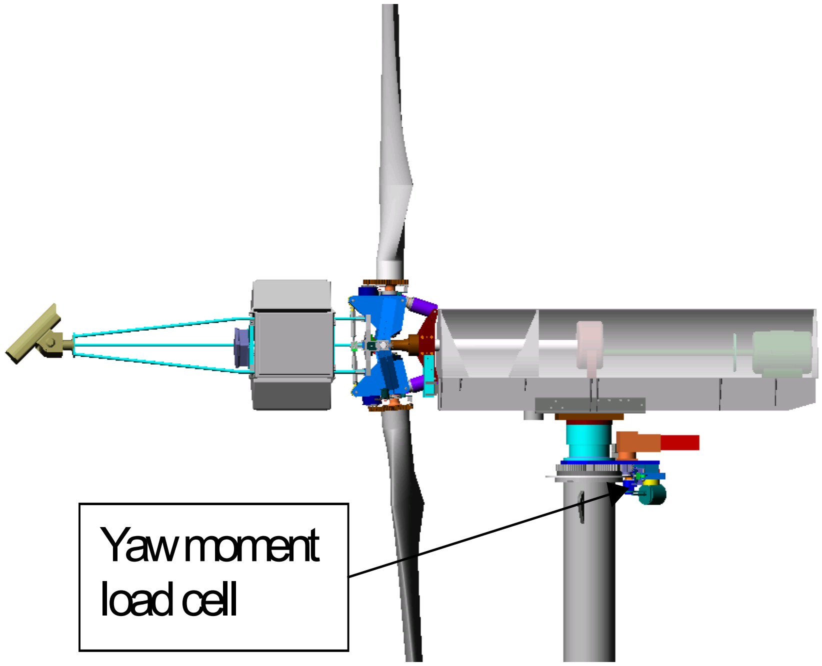
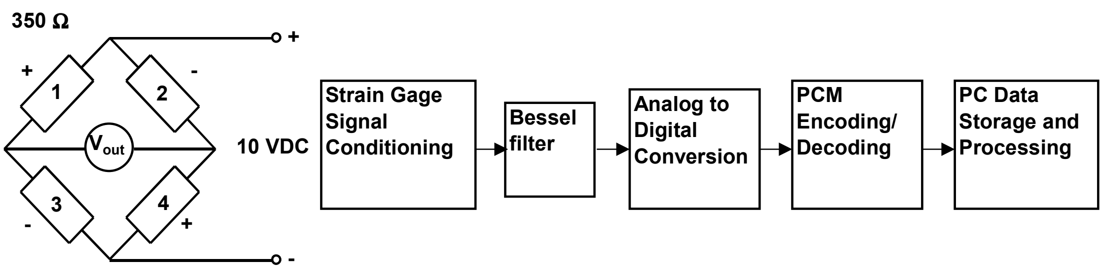


Figure B.2. Yaw moment load cell location.

Strain Gages (Blade Root)

Channel	ID Code	Description
233	B3RFB	Blade 3 root flap bending moment
235	B3REB	Blade 3 root edge bending moment

Location	Pitch shaft (8.6% span), 8360 Steel
Measurement type and units	Bending moment, Nm
Excitation	5Vdc
Range	± 5000με
Resolution	2000 με / V
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc. Model: LWK-09-W250B-350



Note: Flap bending is positive in the downwind direction; Edge bending is positive in the direction of rotation. The physical direction changes from the downwind configuration to the upwind configuration, and the signs of the slope and offset coefficients were adjusted accordingly.

Calibration Procedures

Application of known loads (A1)

A custom jig was used for strain gage calibrations in order to isolate load conditions to one direction only (flap or edge). The jig mounts on the blade at 80% span (1 m inboard of the tip), and the blade is pitched to 1.4° which corresponds to 0° at 80% span. A cord is attached to the jig and run over a pulley to the ground where weights are applied. One person in the man-lift mounts the jig on the blade and positions the man-lift so that the pulley is level and square with the cord attachment to the jig. To calibrate the flap gages, the cord is attached to the jig at a 90° angle to the blade chord. The edge gages are calibrated by attaching the cord to the jig at a point aligned with the blade chord. Another person applies the weights in 20 lb increments from 0 to 120 lb. A third person operates the computer to collect samples at each load condition. The low speed shaft bending gages were calibrated by hanging weights from the boom in a similar manner. These procedures produce new slope values for the strain gage measurements. The pitch encoder gear must be separated from the pitch shaft in order for the load to be transferred solely through the pitch shaft. Loosening the gear may be necessary if hysteresis is apparent.

Determination of the offset values was performed as in previous phases of the experiment. Essentially, the root flap and edge offsets were determined by placing each blade in a position where the respective load is zero. The offset for the low-speed shaft and hub shaft gages was determined by recording cyclic bending moments and torque. The average over one complete rotation was equivalent to the offset under zero load.

The slope and offset values were inserted in a temporary header file called *strains.hdr*. This file is read during the *buildhdr* process, and the values are placed in the *master.hdr* file.

Slope coefficient calibration:

1. The man-lift person notifies ground people which blade and which direction (flap or edge) will be calibrated first. The computer person selects the appropriate channel(s) in *vbl.lst* to place at the top of the file. The number of channels to be collected is specified in the first line with NV, and the PCM stream on which the channels are contained is selected in *gencal.cap*. All of the strain gages are on PCM stream 2 except the yaw moment load cell (NAYM) which is on PCM stream 3. The yaw moment channel (NAYM) is calibrated separately because it is on a different PCM stream than the other strain gages. The low speed shaft torque (LSSTQ) is included with each of the edge bending channels (B1REB, B3REB). The flap bending gages (B1RFB, B3RFB) are each calibrated alone. The low-speed shaft bending gages are calibrated separately (LSSXXB, LSSYYB) by suspending weights from directly hub side of the camera mount at rotor positions corresponding to pure bending for each gage.
2. The *gencal* program is run while the weights are applied from 0 to 120 lb in 20 lb increments with 2 repetitions at each level. When suspending weights from the boom, they are applied from 0 to 100 lb in 20 lb increments with 3 repetitions at each level. *Gencal* is run again while the weights are removed. The recorded weight and count values are stored in the **.cao* input files. A few seconds between application of the weight and collection of data allows any vibrations of the turbine to damp. This is done for both flap and edge directions for each of the blades to calibrate flap bending, edge bending, and low speed shaft torque strain gages as well as the yaw moment load cell. The weights are applied again in each of the above configurations to load the blades in both positive and negative directions. The weights are applied to the boom at rotor positions of 60°, 150°, 240°, and 340° to load the low-speed shaft bending gages in both positive and negative directions.
3. Compute moments in Nm using the following formula:

$$M = \left(\frac{w * \left| R * 39.37 \frac{in}{m} - r \right|}{12 \frac{in}{ft}} \right) 1.35582 \frac{Nm}{ft \cdot lb}$$ where M= Bending moment (Nm),

   w=weight applied (0 to 120 lb), R=Blade radius (5 m), and r=radial distance to strain gage (17 in. from low-speed shaft to blade root gages). The moment arm from the low speed shaft gages to the point on the boom at which the load was applied is 122.325 in. This replaces the term in parentheses in the numerator of the above equation. Plot each curve in Excel, and perform a linear curve fit to determine the slope for both the positive and negative bending conditions for each strain gage. Enter the average of the magnitude of the two slope values in the temporary header file, strains.hdr.

Offset coefficient calibration

1. All of the strain gages were listed in *vbl.lst* for input to *gencal*. The instrumented blade was positioned at 30° increments over one complete rotational cycle. Three samples were

obtained at each position. The blade flap angles were positioned to be equal corresponding to zero teeter angle.

2. The offset for flap bending channels was determined by averaging the count value of each blade at 90° and at 270° where the flap load is 0 Nm. This number may be compared with the value obtained by averaging the loads at 0° and at 180° where the average load should be 0 Nm.
3. A similar procedure provided the offset values of the edge bending channels. The average load at 0° and at 180° provided the zero offset while a comparison of the average load at 90° and 270° indicated if the procedure worked properly.
4. The low-speed shaft bending for both X-X and Y-Y axes and the low speed shaft torque average to zero over the complete rotational cycle. This average count value was used to determine the offset.
5. The yaw moment offset was determined by recording the count value when the yaw brake was released in zero wind conditions.
6. The count values obtained under zero-load conditions for each channel were multiplied by the corresponding slope value and entered in *strains.hdr*.

Note: The calibration pins must be installed during the blade flap pulls to maintain a zero degree flap angle.

Calibration frequency

The strain gage slopes were calibrated prior to wind tunnel testing. The offsets were determined daily during wind tunnel testing.

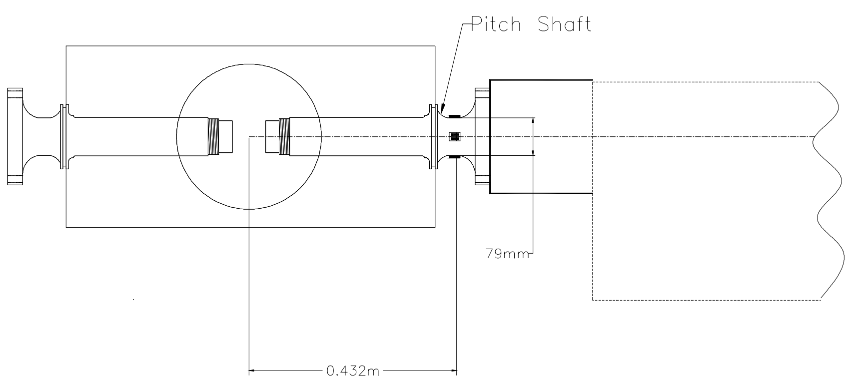


Figure B.3. Root bending gages, side view.

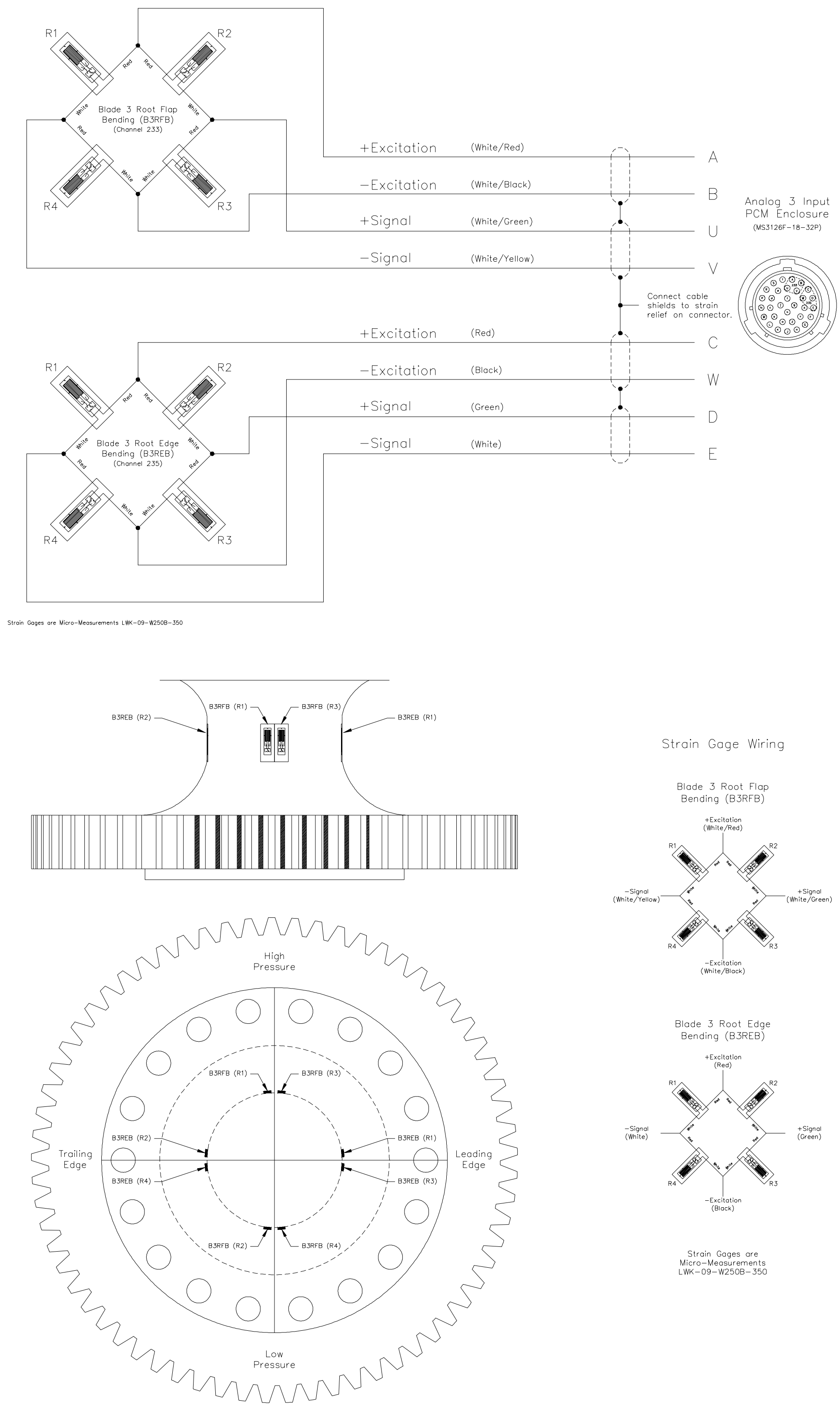
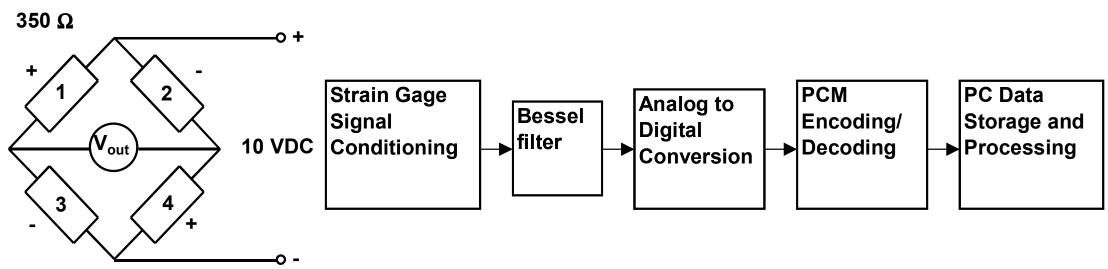


Figure B.4: Blade 3 root bending strain gage configuration.

Strain Gages (Low-speed shaft)

Channel	ID Code	Description
241	LSSTQ	Low-speed shaft torque

Location	Low speed shaft
Measurement type and units	Bending moment, Nm; torque, Nm
Excitation	10 Vdc
Range	± 50,000 με
Resolution	10,000 με / V
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc. Model: CEA-06-250UW-350 (LSS Bending) CEA-06-250US-350 (LSS Torque)



Note: The low-speed shaft XX bending gage has a positive peak when blade 3 is at 240° azimuth and a negative peak when blade 3 is at 60° azimuth for the downwind turbine configuration. The low-speed shaft YY bending gage has a positive peak when blade 3 is at 150° azimuth and a negative peak when blade 3 is at 330° azimuth for the downwind turbine configuration. For the upwind configuration, the low-speed shaft XX bending gage has a positive peak when blade 3 is at 120° azimuth and a negative peak when blade 3 is at 300° azimuth. The YY bending gage reaches a positive peak at blade 3 azimuth 210° and a negative peak at blade 3 azimuth 30° in the upwind configuration. The low-speed shaft torque is positive in the direction of rotation which was clockwise viewed from downwind for the downwind turbine configuration and counter-clockwise for the upwind configuration.

Calibration Procedures (See p. B-3)

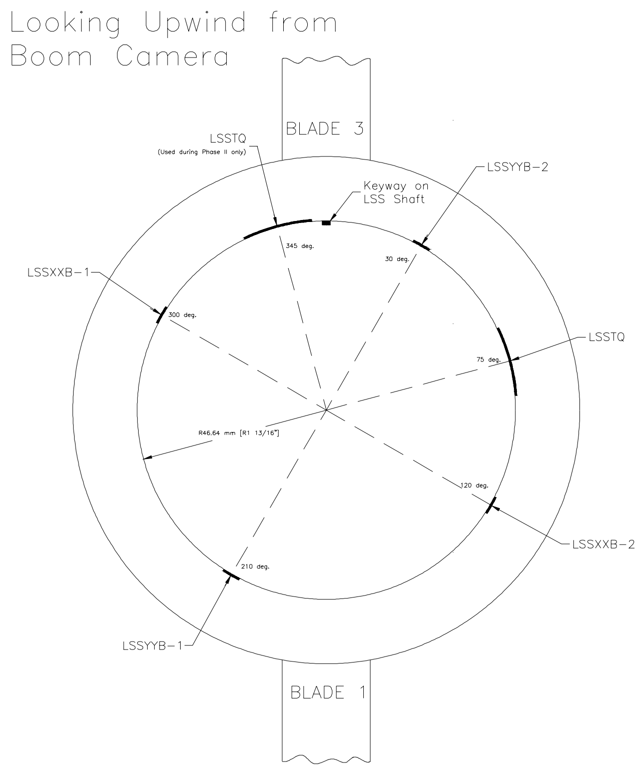
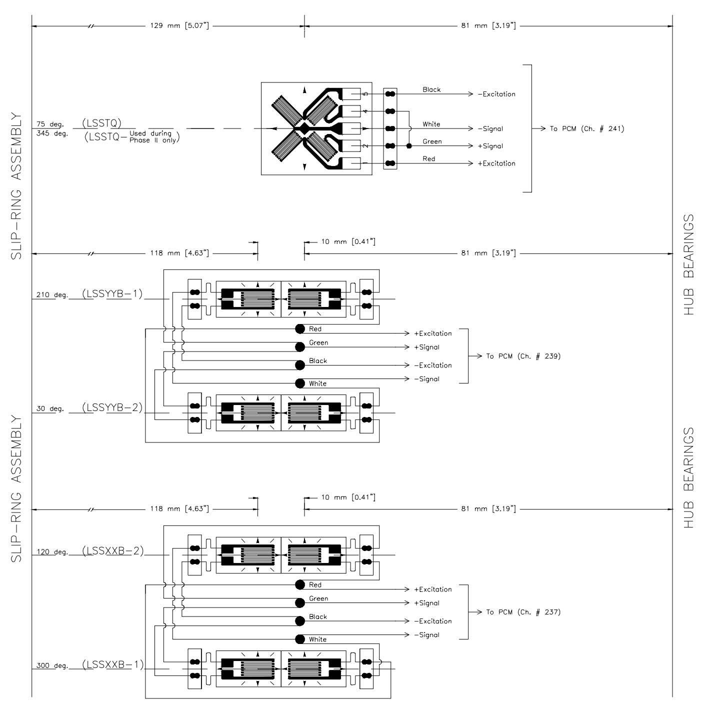


Figure B.5. Low-speed shaft strain gage location (downwind configuration).



LSSTQ (CEA-06-250US-350)
LSSXXB (CEA-06-250UW-350)
LSSYYB (CEA-06-250UW-350)

Figure B.6. Low-speed shaft strain gage configuration (downwind turbine).

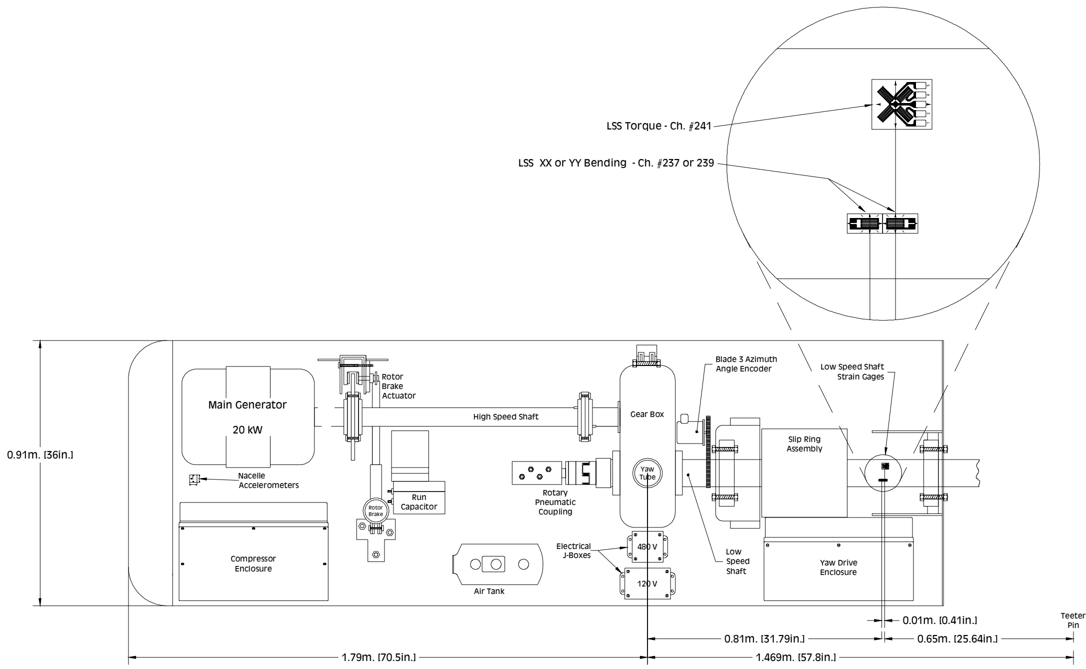
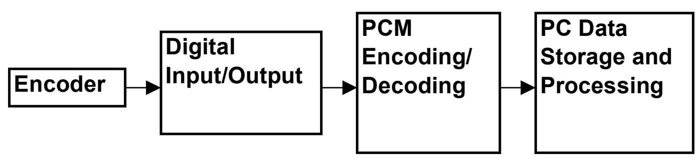


Figure B.7. Low-speed shaft strain gage location within nacelle.

Digital Position Encoders (Rotor)

Channel	ID Code	Description
257	B3PITCH	Blade 3 pitch angle
349	B3AZI	Blade 3 azimuth angle
351	YAW	Turbine yaw angle

Location	Root attachment of each blade; low-speed shaft in nacelle; yaw axis.
Measurement type and units	angular position, degrees
Power Requirement	15 Vdc
Range	360° = 4096 counts
Resolution	0.08789 °/count
Calibration method	Manufacturer specifications (M5) and single point offset determination (S3)
Sensor description	Digital, gray code resolver Accuracy: ±1/2 Count (LSB), worst case BEI Motion Systems Company Model: R25-4096-24 (azimuth only); RAS-25



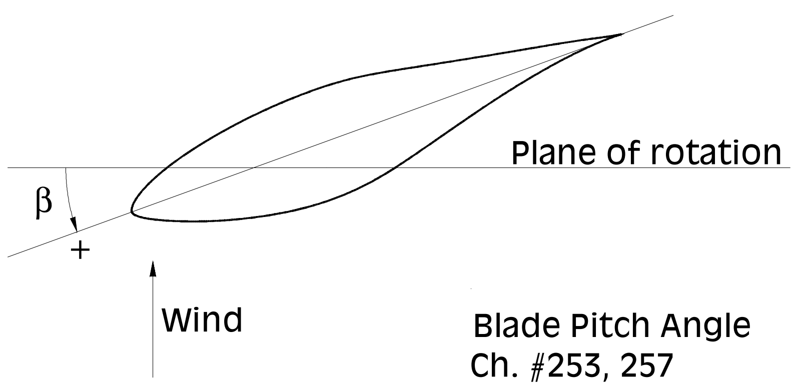


Figure B.8. Blade pitch angle orientation.

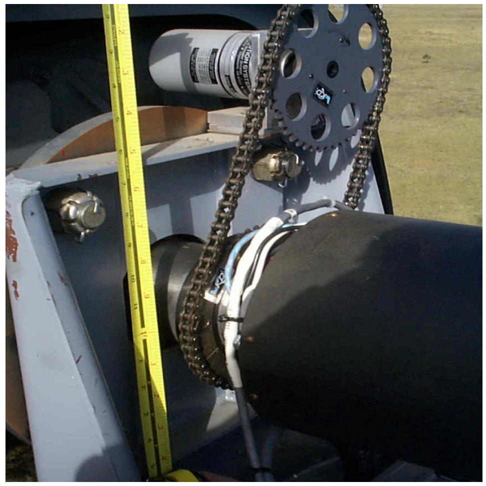


Figure B.9. Azimuth angle encoder.

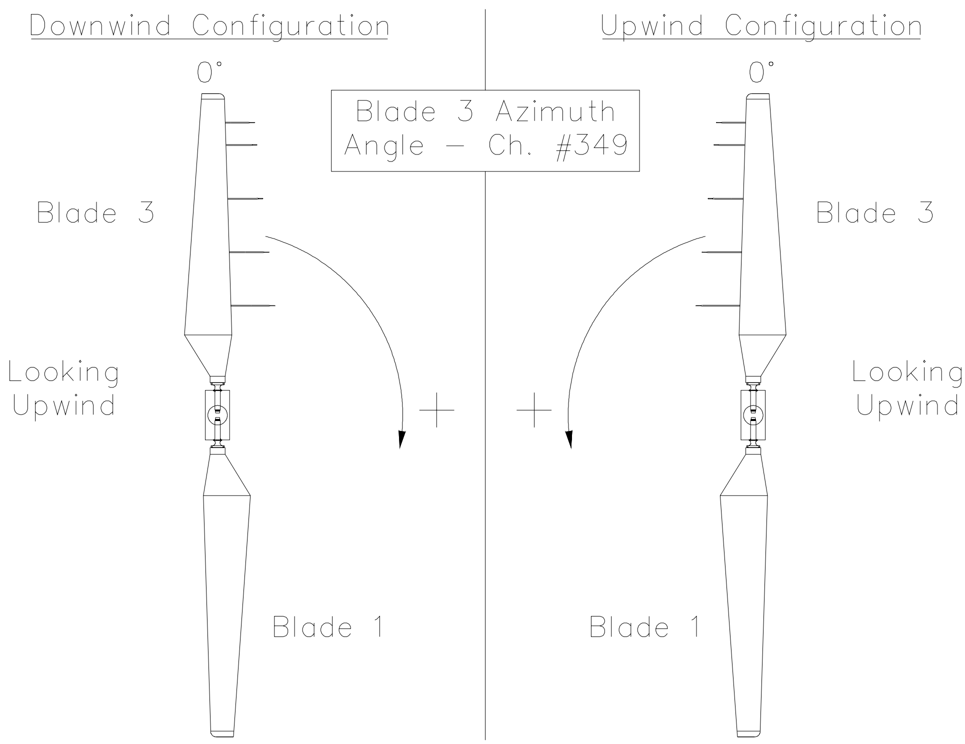


Figure B.10. Azimuth angle measurement convention.

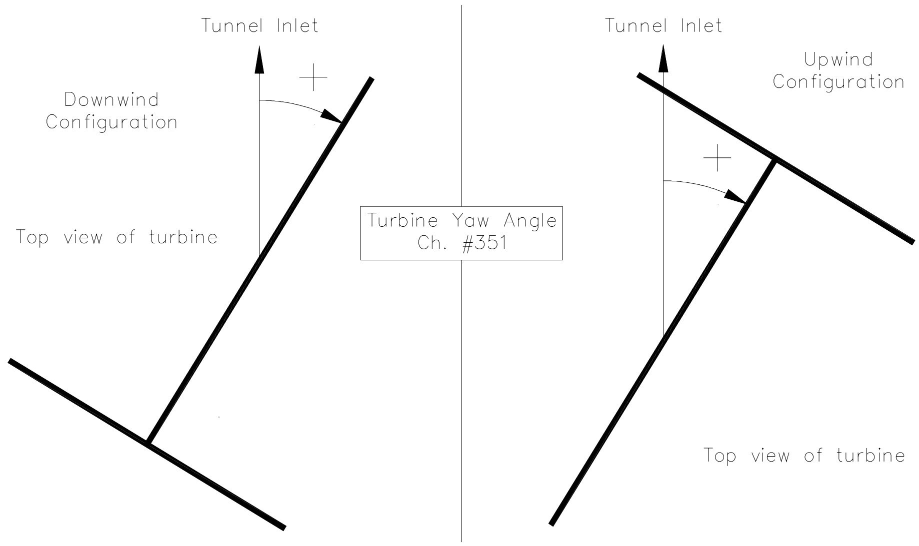


Figure B.11. Yaw angle measurement convention.

Calibration Procedure

Manufacturer specifications - (M5)

1. A calibration was performed by BEI Motion Systems before installation of all digital position encoders.
2. Enter the slope (0.08789°/count) in the appropriate columns of *calconst.xls*.

Single point offset determination - (S3) - (This is a two-person operation requiring one person in the man-lift to position the blades or turbine and one person on the ground to operate the computer.)

1. The man-lift person notifies ground person which encoder is to be calibrated. A reference point is used to determine the offset for each encoder as follows:
   a. Each blade is individually pitched to 0°, and an Angle-star is used to measure the exact pitch angle. The jig is placed on both the upwind and downwind side of the blade and the rotor is positioned at both 90° and 270°. The four pitch measurements, in counts, are averaged together.
   b. The nacelle is aligned by eye with the wind tunnel inlet center strut to determine the yaw angle offset.
   c. The instrumented blade is aligned by eye with the tower (180°) to determine the azimuth angle offset.
2. The difference between the data acquisition system angle and the known angle is determined in counts. This value is added to the current count value listed in *calconst.xls*. A new *master.hdr* file is created using the macros *Write ang.hdr* and *Write convert.v2u* along with the program *vupdate.exe*. The angle is then repositioned and the difference obtained. If the difference is greater than 2-3 counts, the process is repeated.

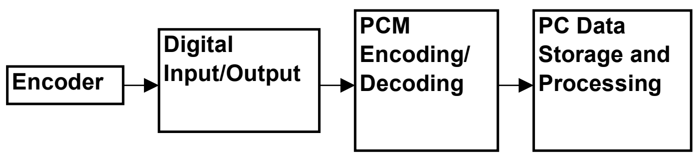
Calibration frequency

The blade pitch, yaw angle, and azimuth angle offsets were determined prior to wind tunnel testing.

Digital Position Encoders (Hub)

Channel	ID Code	Description
255	B3FLAP	Blade 3 flap angle

Location	Mounted on hub outboard of teeter bearing
Measurement type and units	angular position, degrees
Power Requirement	15 Vdc
Range	45° (restricted by damper)
Resolution	0.0110°/count (with 8:1 anti-backlash gearing)
Calibration method	Manufacturer specifications (M4) and single point offset determination (S2)
Sensor description	Digital, gray code resolver Accuracy: ±1/2 Count (LSB), worst case BEI Motion Systems Company Model: RAS-25



Calibration Procedure

Manufacturer specifications - (M4)

1. A calibration was performed by BEI Motion Systems before installation of all digital position encoders.
2. Enter the slope (360 °/(4096 counts*(8 gear-ratio))) in the appropriate columns of *calconst.xls*.

Single point offset determination - (S2) - (This is a two-person operation requiring one person in the man-lift to insert the calibration pins and one person on the ground to operate the computer.)

1. Calibration pins are inserted in each teeter damper individually to position the blades at 0° flap angle.
2. The difference between the data acquisition system angle and the known angle is determined in counts. This value is added to the current count value listed in *calconst.xls*. A new *master.hdr* file is created using the macros *Write ang.hdr* and *Write convert.v2u* along with the program *vupdate*. The angle is then repositioned and the difference obtained. If the difference is greater than 2-3 counts, the process is repeated.

Calibration frequency

The single-point offset determination was done prior to wind tunnel testing.

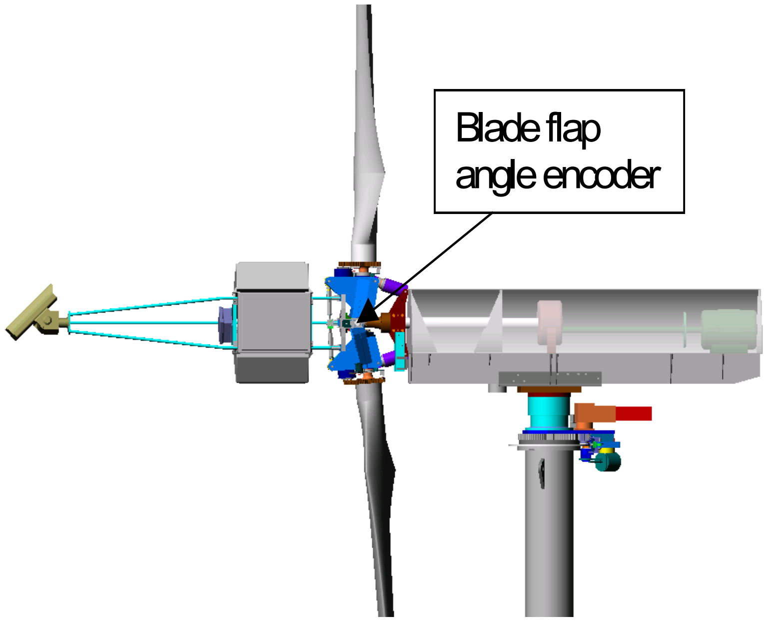


Figure B.12. Blade flap angle encoder location.

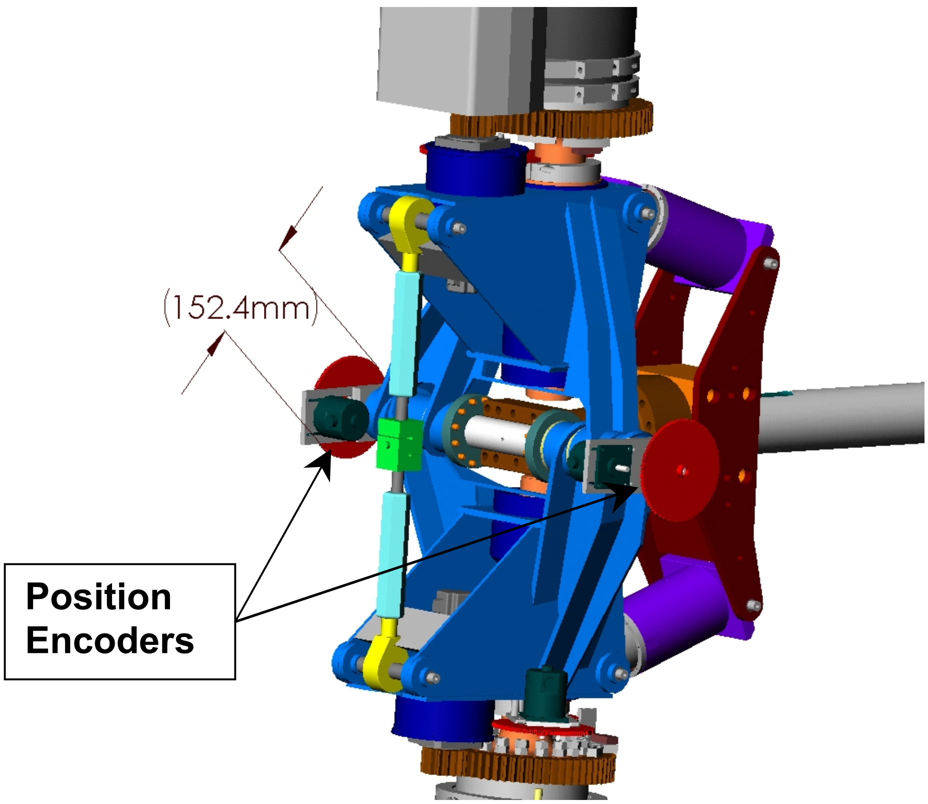


Figure B.13. Blade flap angle encoder close-up view.

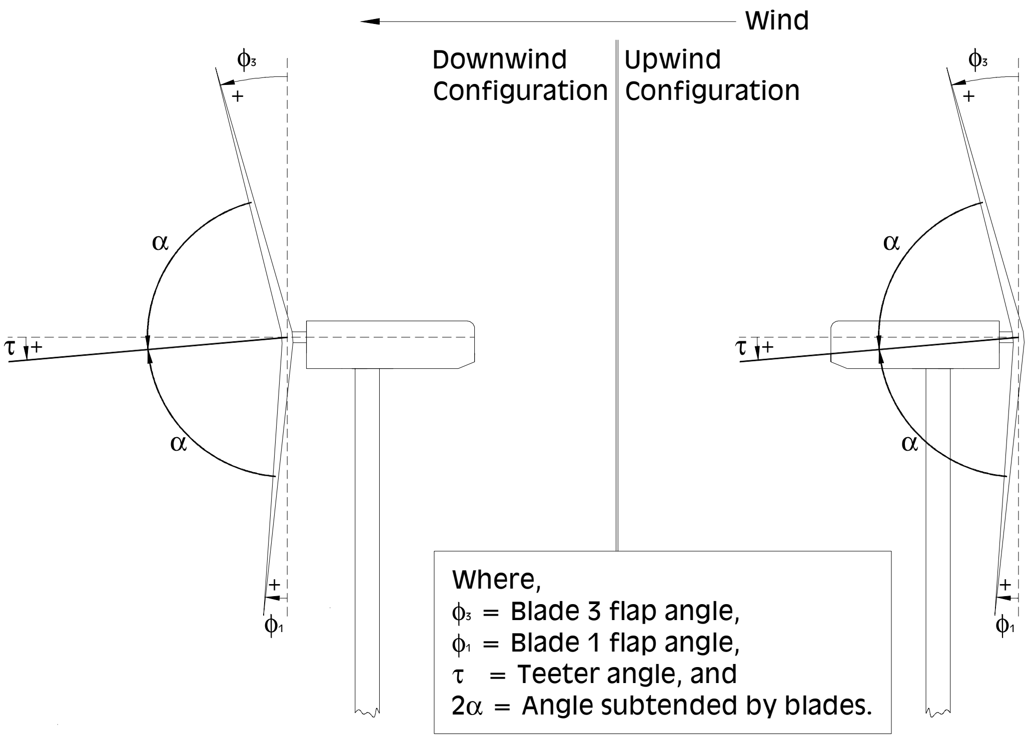
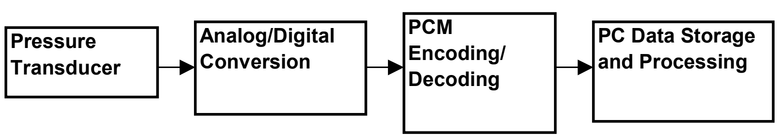


Figure B.14. Blade flap angle convention.

Pressure Transducers (30% and 47% span)

Channel	ID Code	Description
000-050	Ptt30ccc	Surface pressures at 30%, 36%, and 41% span
(even)	Ptt36ccc	tt = transducer tap number
	Ptt41ccc	ccc = % chord pressure tap location
001-051	Ptt47ccc	Surface pressures at 47%, 52%, and 58% span
(odd)	Ptt52ccc	tt = transducer tap number
	Ptt58ccc	ccc = % chord pressure tap location
052-060	5Hx34	5-hole probe at 34% span
(even)		x = designation of hole in 5-hole probe
053-061	5Hx51	5-hole probe at 51% span
(odd)		x = designation of hole in 5-hole probe

Location	Within blade 3 at approximately 30% span and 47% span
Measurement type and units	pressure difference between surface or probe and hub
Power Requirement	5 Vdc, ±12 Vdc
Range	±2500 Pa (10” H_2O) = ±5 V
Resolution	500 Pa/V
Calibration method	Application of known pressures (A2)
Sensor description	32 channel electronic pressure scanner Scan rate: up to 20,000 readings/second Pressure Systems Model: ESP-32SL



Note:

1. Small pressure taps were installed in the surface of the blade skin during manufacturing. Each opening was mounted flush to the airfoil surface and was 0.6731 mm in diameter.
2. Stainless steel tubes, 0.45 m in length, were installed inside the blade’s skin during manufacturing to carry surface pressures to the pressure transducer. A short piece of plastic tubing joined the tubes to the transducers.
3. Gain amplifications and phase effects that occur as a function of tube frequency and tube length were measured. These effects were not significant up to a frequency of 40 Hz, and the measured pressure data showed no appreciable information above 40 Hz (Butterfield et al. 1992).

5-Hole probe positions

The five-hole probes were mounted to a stalk that was aligned with the blade chord. The probes were angled approximately 20° in order to position the tip in the flow. These angles were measured using a custom jig and the Angle Star. Both the relative local flow angle and spanwise flow angles were measured. A machined jig was used to align the holes of the 5-hole probe parallel and perpendicular to the leading edge of the blade. This was done by eye.

For the local flow angle measurement, the blade was placed horizontal to the ground. The jig was placed immediately inboard and immediately outboard of the probe stalk. The angle of the chord relative to the ground was recorded as the local blade angle. A machined surface jig was placed on the 5-hole probe, and another Angle Star was used to measure the angle of the probe relative to the ground. The difference is the angle of the probe relative to the chord of the blade. This was done for all five span locations. The probes were removed and replaced to determine repeatability.

The spanwise flow angles were calibrated similarly. The blade was positioned straight down with 0° coning. The Angle Star was then used to measure the stalk angle and the probe angle relative to the ground. The probe angle listed in Table B.1. is positive inboard of the probe. Note that the probe measures a spanwise flow angle in the plane of the probe, which is not in the plane of the chord.

Table B.1. 5-Hole Probe Angles

Span Location	Local flow angle, degrees	Spanwise flow angle, degrees
34%	22.4	-0.9
51%	19.9	-1.0
67%	22.1	0.7
84%	21.3	-0.7
91%	20.3	-0.4

Calibration Procedures

Application of known pressures - (A2)

This calibration is designed to provide an accurate slope calibration of the complete pressure system. The pressure system controller is invoked to provide NIST-traceable reference pressures at all pressure ports. The pressures ramp up and down across the measurement range. Linear regression provides calibration coefficients that are automatically updated in *master.hdr* before data acquisition. This calibration is performed approximately every 30 minutes.

1. After the turbine has been rotating for 30 minutes, the temperature variations are minimized. A batch file initiates a pressure calibration. The syringe in a hub-mounted instrumentation box (PSC Enclosure, p. B-29) applies a pressure to each transducer at once. Pressures were applied at -0.9, -0.7, -0.5, -0.3, -0.2, -0.1, 0.1, and 0.2 psi. The actual pressure applied to the transducers is measured with the Mensor digital differential pressure transducer. A linear regression analysis provides slope and offset values which are incorporated in *master.hdr*. During consecutive runs, the post-calibration of one data segment may also serve as the pre-calibration for the next data segment.

Table B.2. Pressure Tap Chord Locations

Pressure Tap Number	% chord	Surface	tt	ccc
1	100%	Trailing edge	01	100
4	80%	Upper	04	80U
6	68%	Upper	06	68U
8	56%	Upper	08	56U
11	36%	Upper	11	36U
13	20%	Upper	13	20U
15	10%	Upper	15	10U
17	6%	Upper	17	06U
18	4%	Upper	18	04U
19	2%	Upper	19	02U
20	1%	Upper	20	01U
21	0.5%	Upper	21	.5U
22	0%	Leading edge	22	000
23	0.5%	Lower	23	.5L
24	1%	Lower	24	01L
25	2%	Lower	25	02L
27	6%	Lower	27	06L
30	14%	Lower	30	14L
32	28%	Lower	32	28L
34	44%	Lower	34	44L
36	68%	Lower	36	68L
38	92%	Lower	38	92L

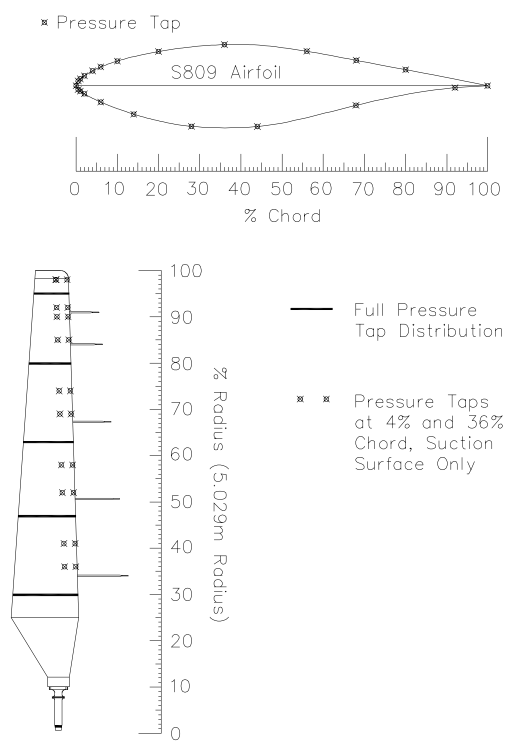


Figure B.15. Tapered-twisted blade planform and pressure instrumentation.

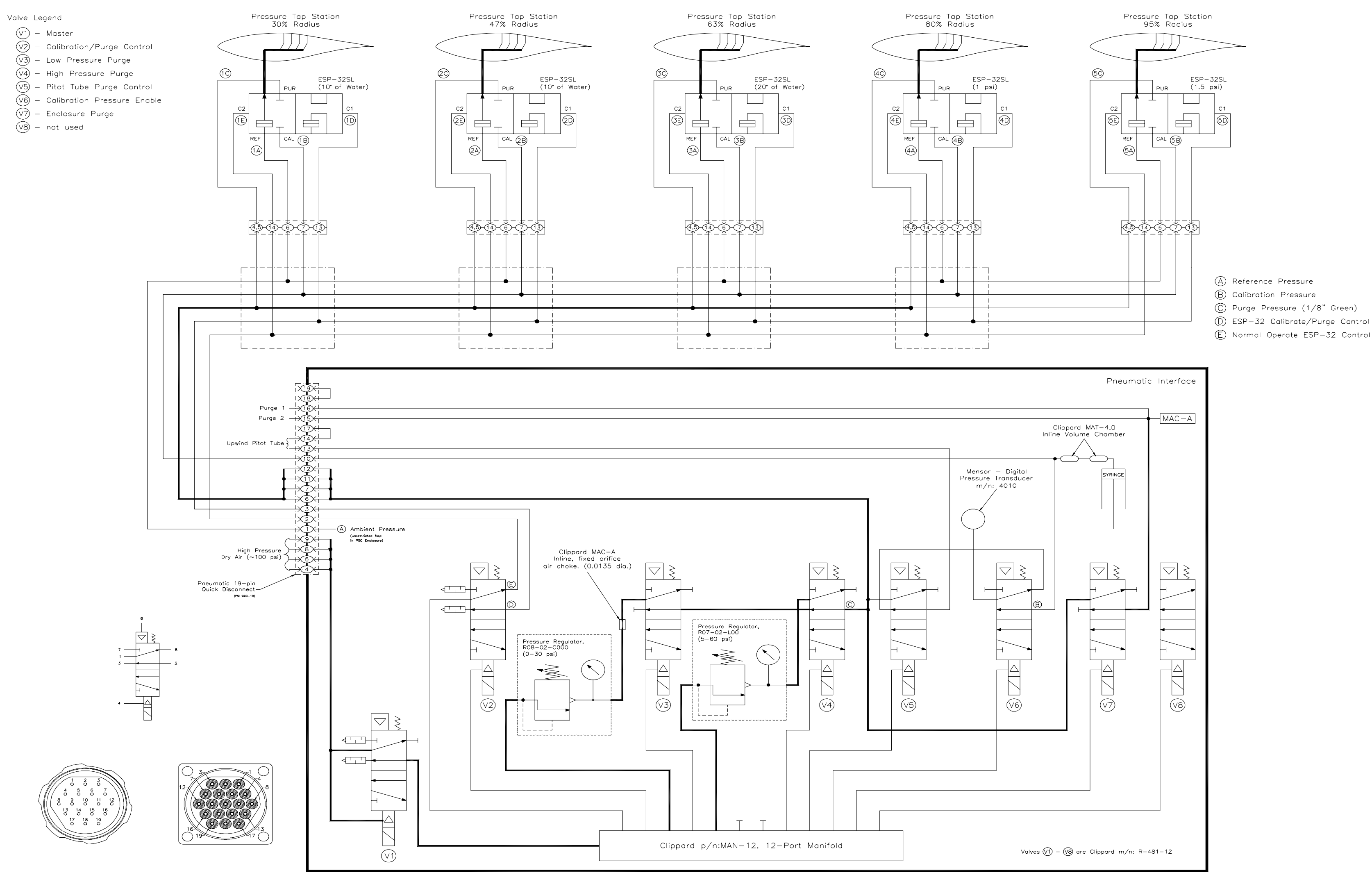


Figure B.16. Pneumatic layout.

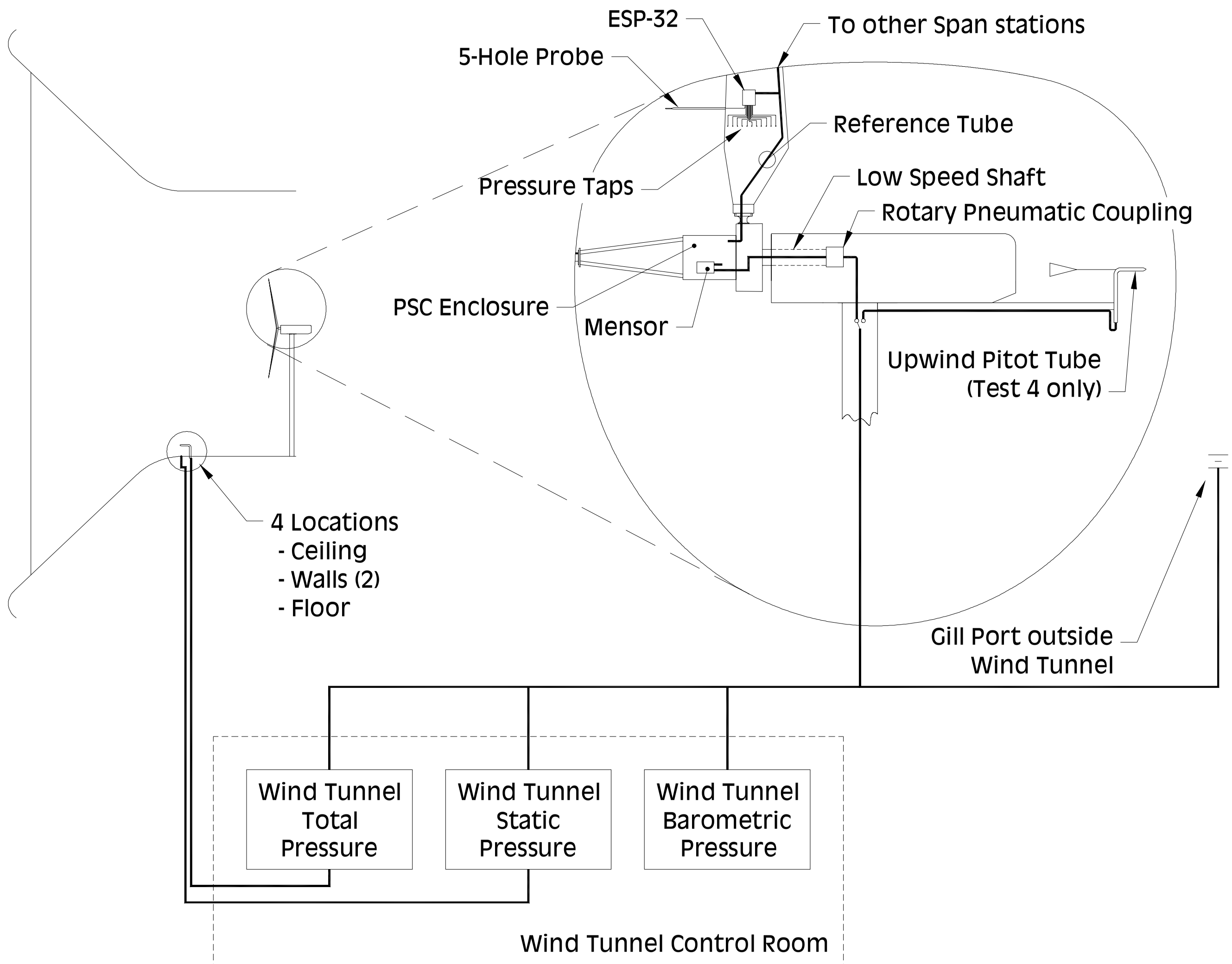


Figure B.17. Pressure system diagram.

Channels derived from pressure measurements

Wind Tunnel Parameters

NASA provided equations to correct the measured total and static pressures from inlet pressures to test section pressures and to compute the dynamic pressure, wind speed and air density. Although all output parameters are in metric units, the equations provided by NASA assume IP units. The measured parameters were converted to IP units with MUNCH. The corrected and calculated values were obtained in IP units and subsequently converted to metric units for output. Table B.3 lists the output channels computed using the measurements provided with NASA instrumentation.

Table B.3. Wind tunnel computed parameters

Channel	Channel ID	Description	Units
857	VTUN	Tunnel velocity	m/s
858	QTUN	Tunnel dynamic pressure	Pa
859	RHOTUN	Tunnel air density	kg/m^3
860	PTTUN	Tunnel total pressure	Pa
861	PSTUN	Tunnel static pressure	Pa
862	PATUN	Tunnel centerline pressure	Pa

The tunnel centerline pressure was computed by correcting the measured atmospheric pressure with the height differential between the gill port and the tunnel centerline. Although the equations provided by NASA indicate that the static pressure at the inlet must be corrected to obtain test section static pressure, this was deemed unnecessary after a NASA calibration in December 1999 (Zell, 2000). The measured total and static pressures were added to the corrected tunnel centerline pressure to obtain absolute pressures. The air density was computed using the measured dew point temperature (WTDPT), the measured tunnel air temperature (WTT18M), the corrected atmospheric pressure, and the tunnel static pressure. The tunnel dynamic pressure was computed using the total and static pressures as follows:

$$QTUN = 0.7 * PSTUN * 5 * \left(\left(\frac{PTTUN}{PSTUN} \right)^{2/7} - 1 \right) \qquad \text{Eq. (1)}$$

This equation is exact for air and accounts for compressibility. The tunnel velocity is computed using the air density and dynamic pressure.

$$VTUN = \sqrt{2 * \frac{QTUN}{RHOTUN}} \qquad \text{Eq. (2)}$$

Mensor Differential Pressure Transducer

The Mensor differential pressure transducer is a digital instrument. It generates a 16-bit signal, but each channel in the data system is 12 bits. Thus, two channels were used to transmit the 16-bit, digital signal output from the Mensor. These two channels were combined in MUNCH to obtain the measured pressure in engineering units. Table B.4 contains the engineering unit channel computed by MUNCH from the two data channels.

Table B.4. Mensor differential pressure transducer channels

Channel	Channel ID	Description	Units
815	MENSOR	Mensor	Pa

The Mensor measured differential pressure between the PSC Enclosure and the NASA gill port pressure reference.

Pressure Measurement Path

All of the ESP-32 pressure transducers located inside the instrumented blade were referenced to the PSC Enclosure. These transducers measured the differential pressure between a pressure tap (P_{tap}) and the instrumentation box (P_{box}) or one port of the 5-hole probe and the instrumentation box. The Mensor measured the differential pressure between the instrumentation box and the gill port atmospheric pressure (P_{atm}) or the instrumentation box and the upwind static probe (P_{statpr}). The wind tunnel inlet was instrumented to measure the pressure differential between the static pressure at the inlet (P_{static}) and the gill port atmospheric pressure. Recall that the recent calibration performed by NASA concluded that the static pressure at the inlet was also the test section static pressure. Combining these pressure differentials as follows, all pressure measurements were made in reference to static pressure.

$$P_{tap} - P_{static} = [P_{tap} - P_{box}] + [P_{box} - P_{atm}] - [P_{static} - P_{atm}] \qquad \text{Eq. (2)}$$

These equations were implemented in MUNCH for each pressure tap measurement and each port of the 5-hole probes.

Centrifugal Force Correction

The differential pressures between the blade surface pressure and the PSC Enclosure were reduced by the centrifugal force acting on the column of air in the reference pressure tube caused by rotation of the blade. This force was added to each measured pressure data value per Equations (3) and (4). Each of the probe pressures was also corrected in this manner.

$$P_{meas} = [P_{tap} - P_{box}] + P_{cent} \;, \qquad (3)$$

$$P_{cent} = \frac{1}{2} RHOTUN\left(r * RPM\right)^2 \text{, and} \qquad (4)$$

where
P_{meas} = differential pressure corrected for centrifugal force (Pa),
P_{cent} = centrifugal force correction (Pa),
r = radial distance to surface pressure tap or 5-hole probe (m),

Dynamic Pressure

Because all pressure measurements were referenced to static pressure, direct measurement of dynamic pressure was possible. One measure of dynamic pressure is the stagnation point pressure at each of the full-chord pressure tap locations. The pressure tap at each primary span location where the static pressure attains a maximum was considered to be the stagnation point, and the corresponding pressure at that location was used as the stagnation pressure. The resolution of the pressure taps on the lower surface was assumed sufficient to extract the maximum positive surface pressure, especially at lower angles of attack. According to Shipley et al. (1995) the stagnation point method is the preferred method of estimating dynamic pressure on the blade. This measurement of dynamic pressure was used to normalize each of the blade surface pressures and is thus referred to as the normalization pressure. Table B.5 also includes these dynamic pressure measurements.

Table B.5. Dynamic Pressure Measurements

Channel	Channel ID	Description	Units
822	QNORM30	Normalization Factor at 30% Span	Pa
828	QNORM47	Normalization Factor at 47% Span	Pa
834	QNORM63	Normalization Factor at 63% Span	Pa
840	QNORM80	Normalization Factor at 80% Span	Pa
846	QNORM95	Normalization Factor at 95% Span	Pa

Pressure Coefficients

Each of the corrected blade surface pressure values was normalized by the stagnation pressure at the corresponding span location as shown in Equation (6). These values were recorded in the engineering unit files for each pressure tap.

$$C_p = \frac{P_{meas}}{Q_{norm}}; \tag{6}$$

where

C_p = pressure coefficient, dimensionless,
P_{meas} = differential pressure corrected for centrifugal force (Pa), and
Q_{norm} = stagnation point dynamic pressure corrected for centrifugal force (Pa).
The intermediate taps were normalized with a dynamic pressure that was linearly interpolated between the two adjacent full-chord pressure tap locations.

Aerodynamic Force Coefficients

The pressure distributions for rotating-blade data were integrated to compute normal force coefficients (C_N) and tangential force coefficients (C_T). They represent the forces acting perpendicular and parallel to the airfoil chord, respectively. The average pressure between two adjacent taps was first projected onto the chord line, integrated to determine the C_N values, and then projected onto an axis orthogonal to the chord and integrated to compute C_T values. This procedure is described in detail by Rae and Pope (1984). Equations (7) and (8) give the integration procedure used to determine C_N and C_T. The x and y values begin at the trailing edge (x = 1), proceed forward over the upper surface of the blade, and then aft along the bottom surface, ending at the starting point, the trailing edge.

$$C_N = \sum_{i=1}^{\#oftaps} \left(\frac{C_{p_i} + C_{p_{i+1}}}{2} \right) \left(x_{i+1} - x_i \right), \text{ and} \tag{7}$$

$$C_T = \sum_{i=1}^{\#oftaps} \left(\frac{C_{p_i} + C_{p_{i+1}}}{2} \right) \left(y_{i+1} - y_i \right); \tag{8}$$

where,

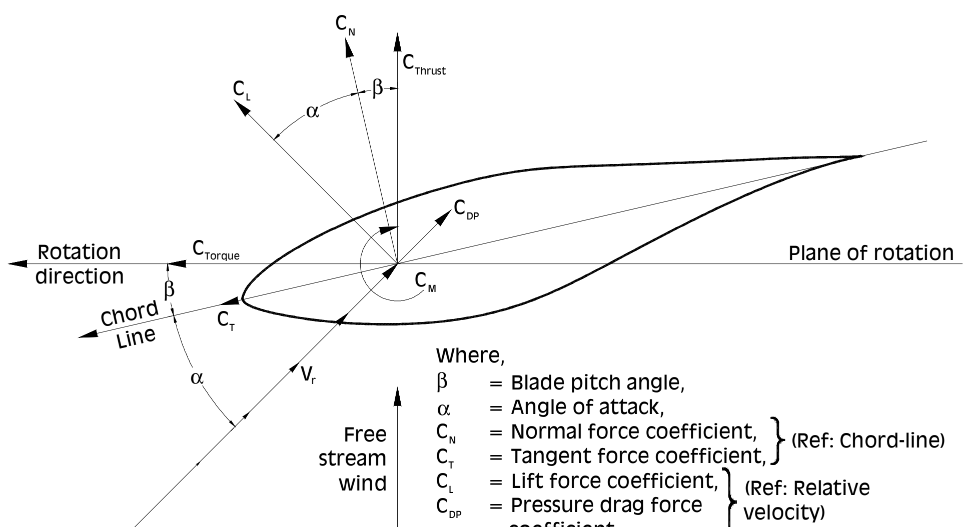
C_p = normalized pressure coefficient
x_i = normalized distance along chord line from leading edge to i^{th} pressure tap
y_i = normalized distance from chord line along axis orthogonal to chord to i^{th} pressure tap
In a similar integral procedure, pitching moment coefficients (C_M) were determined. The pitching moment represents the total moment about the 1/4 chord due to the normal and tangential forces at a pressure tap with the vertical or horizontal distance from the pitch axis as the moment arm. Note that the pitch and twist axis is at 30% chord. This equation follows:

$$C_M = -\sum_{i=1}^{\#oftaps} \left[\left(\frac{C_{p_i} + C_{p_{i+1}}}{2} \right) \left[\left(x_{i+1} - x_i \right) \left(\frac{x_{i+1} - x_i}{2} + x_i - 0.25 \right) + \left(y_{i+1} - y_i \right) \left(\frac{y_{i+1} - y_i}{2} + y_i \right) \right] \right]. \tag{9}$$

All of the aerodynamic force coefficients are listed in Table B.6 and illustrated in Figure 10.

Table B.6. Aerodynamic Force Coefficients

Channel	Channel ID	Description	Units
817	CN30	Normal Force at 30% Span	Cn
818	CT30	Tangent Force at 30% Span	Ct
821	CM30	Pitch Moment Coeff at 30% Span	Cm
823	CN47	Normal Force at 47% Span	Cn
824	CT47	Tangent Force at 47% Span	Ct
827	CM47	Pitch Moment Coeff at 47% Span	Cm
829	CN63	Normal Force at 63% Span	Cn
830	CT63	Tangent Force at 63% Span	Ct
833	CM63	Pitch Moment Coeff at 63% Span	Cm
835	CN80	Normal Force at 80% Span	Cn
836	CT80	Tangent Force at 80% Span	Ct
839	CM80	Pitch Moment Coeff at 80% Span	Cm
841	CN95	Normal Force at 95% Span	Cn
842	CT95	Tangent Force at 95% Span	Ct
845	CM95	Pitch Moment Coeff at 95% Span	Cm

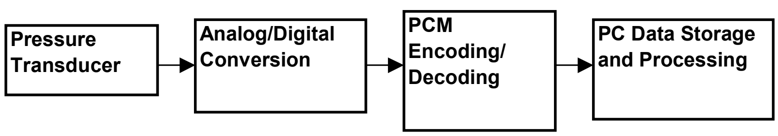


Where,
β = Blade pitch angle,
α = Angle of attack,
C_N = Normal force coefficient,
C_T = Tangent force coefficient, } (Ref: Chord-line)
C_L = Lift force coefficient,
C_{DP} = Pressure drag force coefficient, } (Ref: Relative velocity)
C_{Thrust} = Thrust coefficient,
C_{Torque} = Torque coefficient, } (Ref: Plane of rotation)
C_M = Pitch moment coefficient, and } (Ref: Quarter-chord)
V_r = Resultant Velocity Vector.

Figure 18. Aerodynamic force coefficient conventions.

Channel	ID Code	Description
100-150	Ptt63ccc	Surface pressures at 63%, 69%, and 74% span
(even)	Ptt69ccc	tt = transducer tap number
	Ptt74ccc	ccc = % chord pressure tap location
152-160	5Hx67	5-hole probe at 67% span
(even)		x = designation of hole in 5-hole probe

Location	Within blade 3 at approximately 63% span
Measurement type and units	pressure difference between surface or probe and hub
Power Requirement	5 Vdc, ±12 Vdc
Range	±5000 Pa (20” H_2O) = ±5 V
Resolution	1000 Pa / V
Calibration method	Application of known pressures (A2)
Sensor description	32 channel electronic pressure scanner Scan rate: up to 20,000 readings/second Pressure Systems Model: ESP-32SL

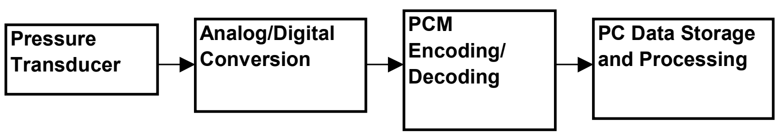


Calibration Procedure (See p. B-17)

Pressure Transducers (80% span)

Channel	ID Code	Description
101-151 (odd)	Ptt80ccc Ptt85ccc Ptt90ccc	Surface pressures at 80%, 85%, and 90% span tt = transducer tap number ccc = % chord pressure tap location
153-161 (odd)	5Hx84	5-hole probe at 84% span x = designation of hole in 5-hole probe

Location	Within blade 3 at approximately 80% span
Measurement type and units	pressure difference between surface or probe and hub
Power Requirement	5 Vdc, ±12 Vdc
Range	±6894 Pa, (1.0 psi) = ±5 V
Resolution	1379 Pa / V
Calibration method	Application of known pressures (A2)
Sensor description	32 channel electronic pressure scanner Scan rate: up to 20,000 readings/second Custom made for ±1.0 psi range Pressure Systems Model: ESP-32SL

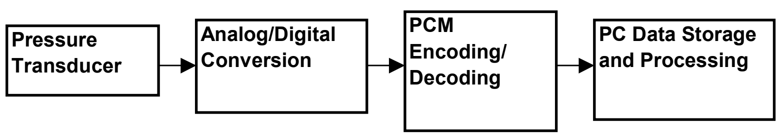


Calibration Procedure (See p. B-17)

Pressure Transducers (95% span)

Channel	ID Code	Description
200-250	Ptt95ccc	Surface pressures at 95%, 92%, and 98% span
(even)	Ptt92ccc	tt = transducer tap number
	Ptt98ccc	ccc = % chord pressure tap location
252-260	5Hx91	5-hole probe at 91% span
(even)		x = designation of hole in 5-hole probe

Location	Within blade 3 at approximately 95% span
Measurement type and units	pressure difference between surface or probe and hub
Power Requirement	5 Vdc, ±12 Vdc
Range	±10,342 Pa (1.5 psi) = ±5 V
Resolution	2068 Pa / V
Calibration method	Application of known pressures (A2)
Sensor description	32 channel electronic pressure scanner Scan rate: up to 20,000 readings/second Custom made for ±1.5 psi range Pressure Systems Model: ESP-32SL

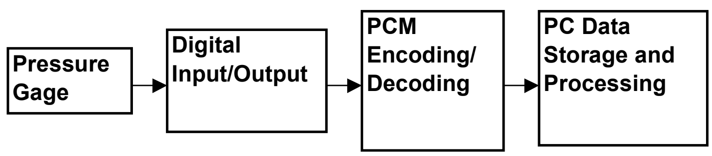


Calibration Procedure (See p. B-17)

Digital Differential Reference Pressure

Channel	ID Code	Description
259	MENS1	Digital first 12 bits from Δ pressure
261	MENS2	Digital last 12 bits from Δ pressure

Location	Rotor package, PSC enclosure
Measurement type and units	Calibration reference pressure and static differential pressure, Pa
Power Requirement	12 Vdc
Range	±2 psig (±13,790 Pa)
Resolution	0.42 Pa/bit
Calibration method	Manufacturer (M3)
Sensor description	Digital pressure transducer 16 bit binary output Accuracy: 0.01% full scale Mensor Corporation Model: 4010



Calibration Procedure

Manufacturer specifications - (M3)

1. A calibration was performed by Mensor Corporation before installation of either digital pressure transducer.
2. The zero offset was determined by disconnecting the reference pressure tubing which provided the instrumentation box pressure to both sides of the Mensor. The tare value was adjusted to eliminate the difference.

Calibration frequency

The differential pressure transducers were calibrated by the manufacturer prior wind tunnel testing. The zero offset was determined daily during the wind tunnel test.

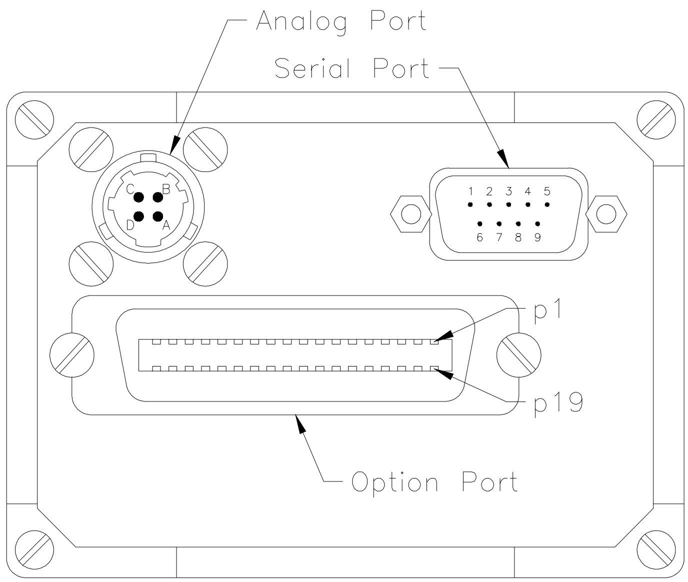


Figure B.19. Mensor electrical ports.

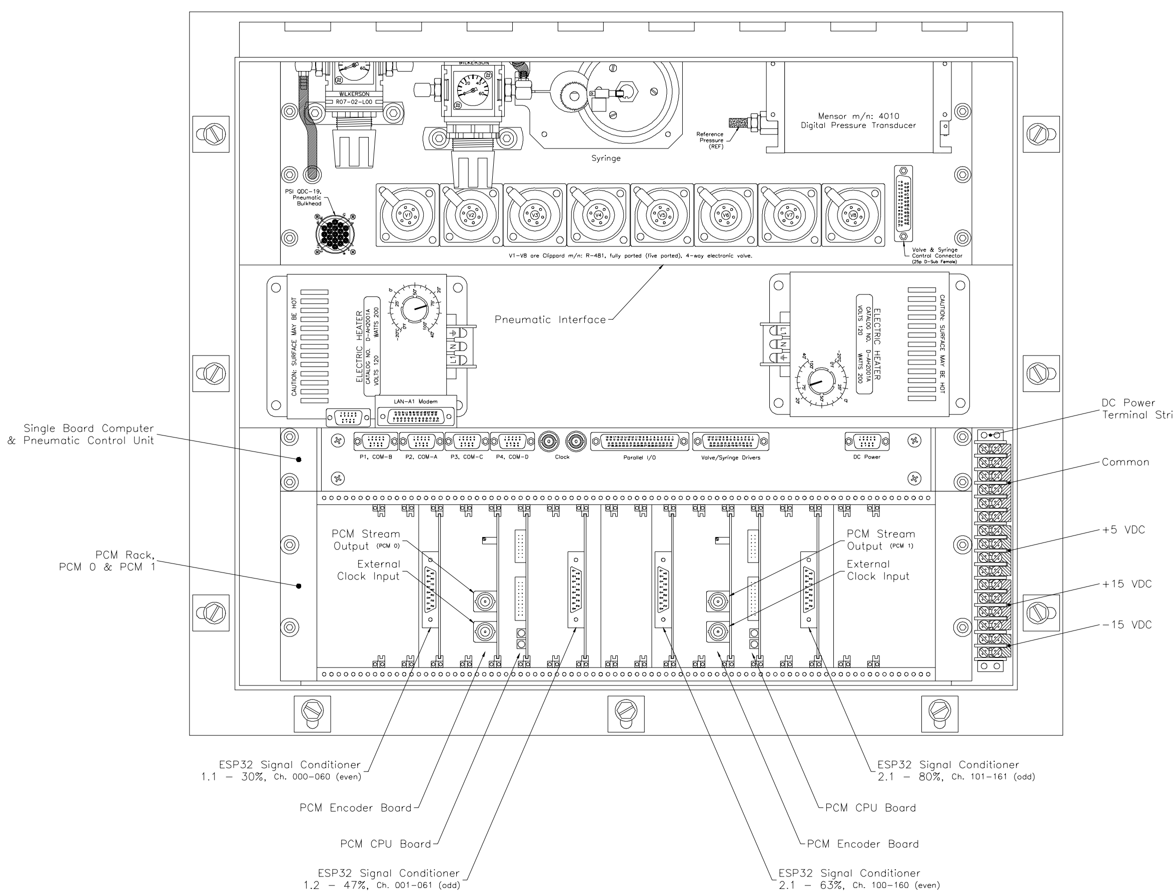
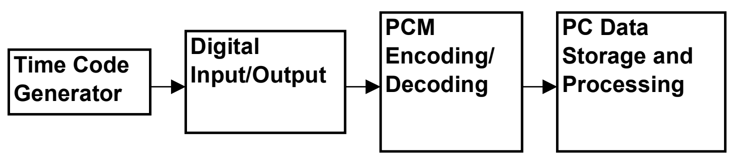


Figure B.20. Pressure System Controller (PSC) Enclosure.

Time Code Generator

Channel	ID Code	Description
353	DAY	Clock - day
355	HOUR	Clock - hour
357	MINUTE	Clock - minute
359	SECOND	Clock - second
361	MILLISEC	Clock - millisecond

Location	PCM rack in data shed
Measurement type and units	Time, day, hour, minute, second, and millisecond
Power Requirement	120 V AC
Calibration method	Manufacturer (M2)
Sensor description	Time code generator formats: IRIG-A, IRIG-B, IRIG-C, IRIG-E, IRIG-H frequency stability: ±5ppm Model: 9310-804



Calibration Procedure

Manufacturer specifications - (M2)

1. A calibration was performed by the manufacturer before installation.

Calibration frequency

The time code generator was calibrated prior to Phase III data collection. However, prior to each series of data collection (or in the event of a power failure) the clock was set using atomic clock readings.

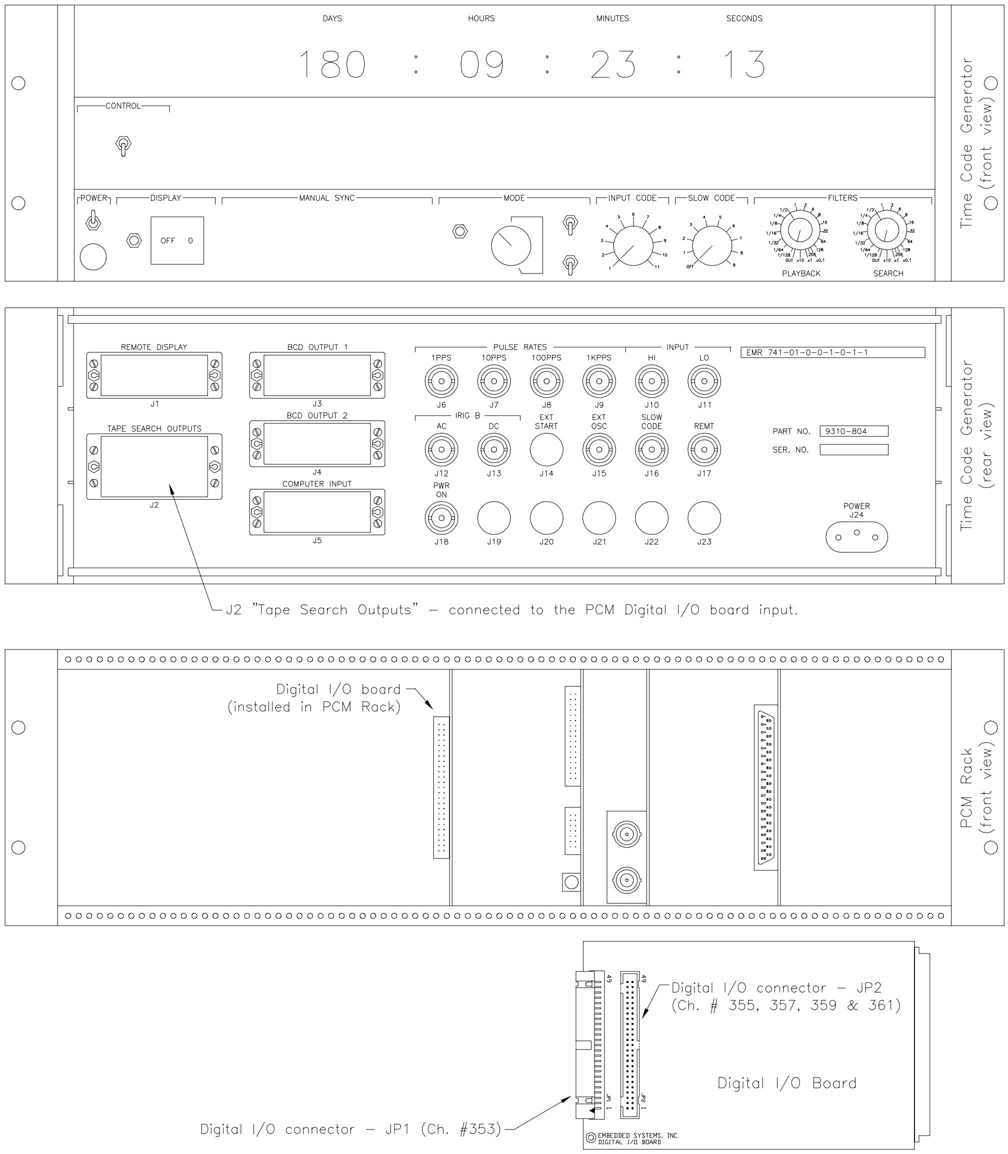


Figure B.21. Time code generator.

Strain Gage Signal Conditioning

Channel	Description
215-241 (odd)	Blade root, yaw moment, hub shaft, and low-speed shaft strain gages; teeter damper and teeter link load cells
Location	Rotor package
Input level	Isolated strain gage input
Output level	± 5 Vdc
Description	
	Analog Devices, Inc. Model: 5B01 (backplate), 5B38-01 (input module)

Butterworth Filter

Channel	Description
300-334 (even), 342	low-pass, 6^{th} order, Butterworth 10 Hz filter
Location	PCM rack
Description	Differential low-pass filter 5V power requirement passband remains flat until 0.7 of Fc (-3 dB frequency), and then roll-off monotonically at a rate of 36 dB/oct
	Frequency Devices Model: 5BAF-LPBU6-10Hz

Bessel Filter

Channel	Description
336-340 (even), 344-358 (even)	low-pass, 6^{th} order, Bessel 100 Hz filter
Location	PCM rack; rotating instrumentation package
Description	Differential low-pass filter 5V power requirement passband remains flat until 0.1 Fc, and then roll-off monotonically to 20 dB at 2.5 Fc
	Frequency Devices Model: 5BAF-LPBE6-100Hz

Note: Yaw moment (342) channel uses a Butterworth, filter but all other strain gages use a Bessel filter.

Analog / Digital Conversion

Channel	Description
000-061, 100-161, 200-260 (even), 201-241 (odd), 300-358 (even)	All analog channels
Location	PCM rack; rotating instrumentation package
Description	Instrumentation amplifier gain 0.9 Sample and hold capability 7 µs, 12-bit analog to digital conversion 4.250 V reference with 10 ppm accuracy that is adjusted within ±2mV Custom built by Embedded Systems

Digital Input / Output

Channel	Description
251-261 (odd), 349-361 (odd)	Position encoders, time code generator
Location	PCM rack; rotating instrumentation package
Description	Digital parallel Custom built by Embedded Systems

Channel	Description
All channels	Encode/decode digital data
Location	PCM rack in data shed; rotating instrumentation package
Encode	CPU encoder board with 400 kbits/sec capability Encodes 24 bits at one time; no storage capacity Bi-Phase L Filtered at 400 kHz Signal level ±2.5 V Custom built by Embedded Systems
Decode	Phase lock loop Software set buffer size which uses direct memory access (DMA) to place data in computer memory when the buffer is full Number of buffers is also variable Custom built by Apex Systems

Analog Devices 5B Module Specifications:
5B38-02 ±30mV Input, ±5V Output, +10V Excitation
5B41-01 ± 1V Input, ±5V Output, No Excitation
5B41-03 ±10V Input, ±5V Output, No Excitation

Figure B.22. Rotor based PCM enclosure.

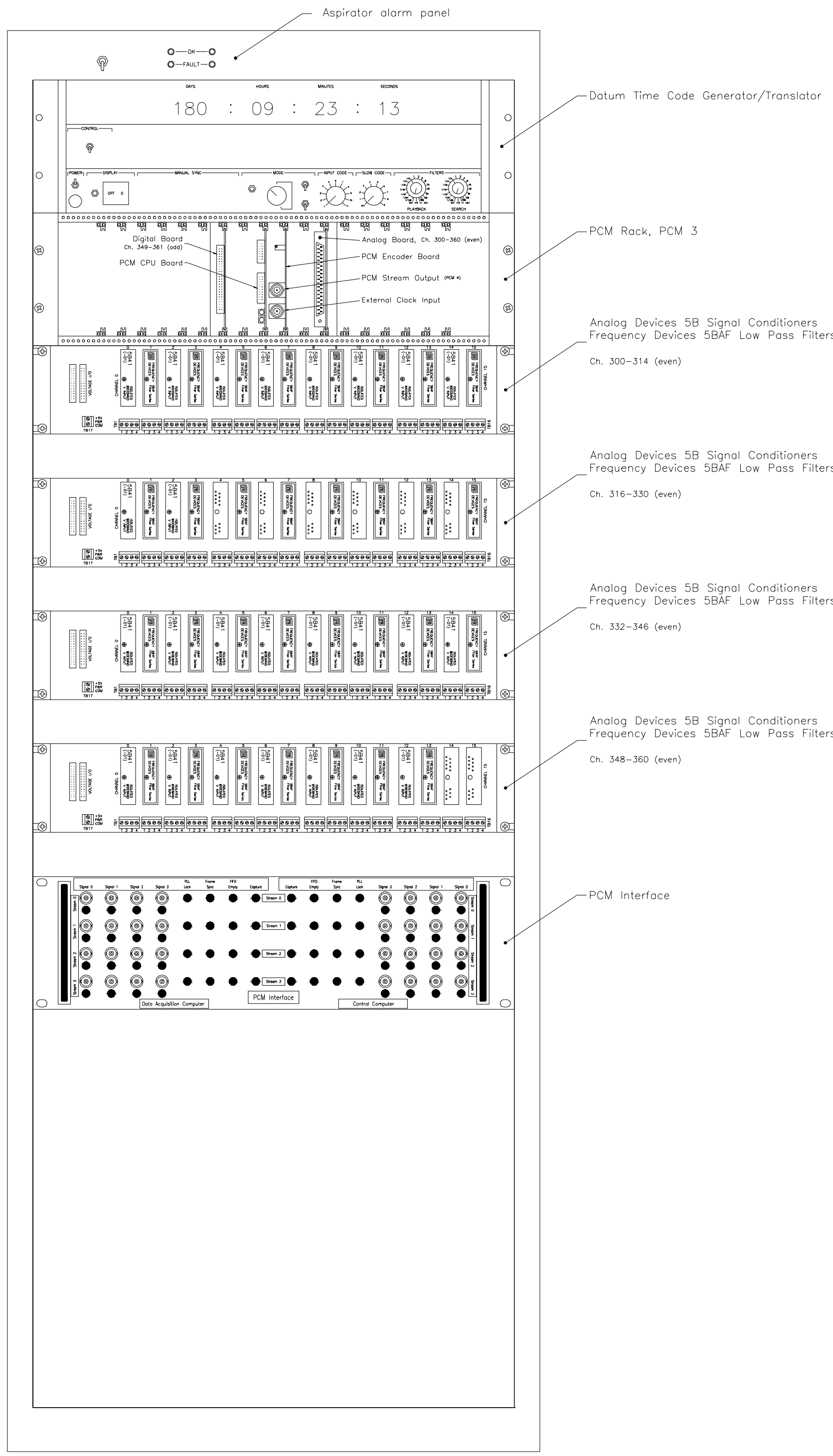


Figure B.23. Ground based PCM rack.